Medium reponse in AMPT

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Jet Quenching in the Quark-Gluon Plasma

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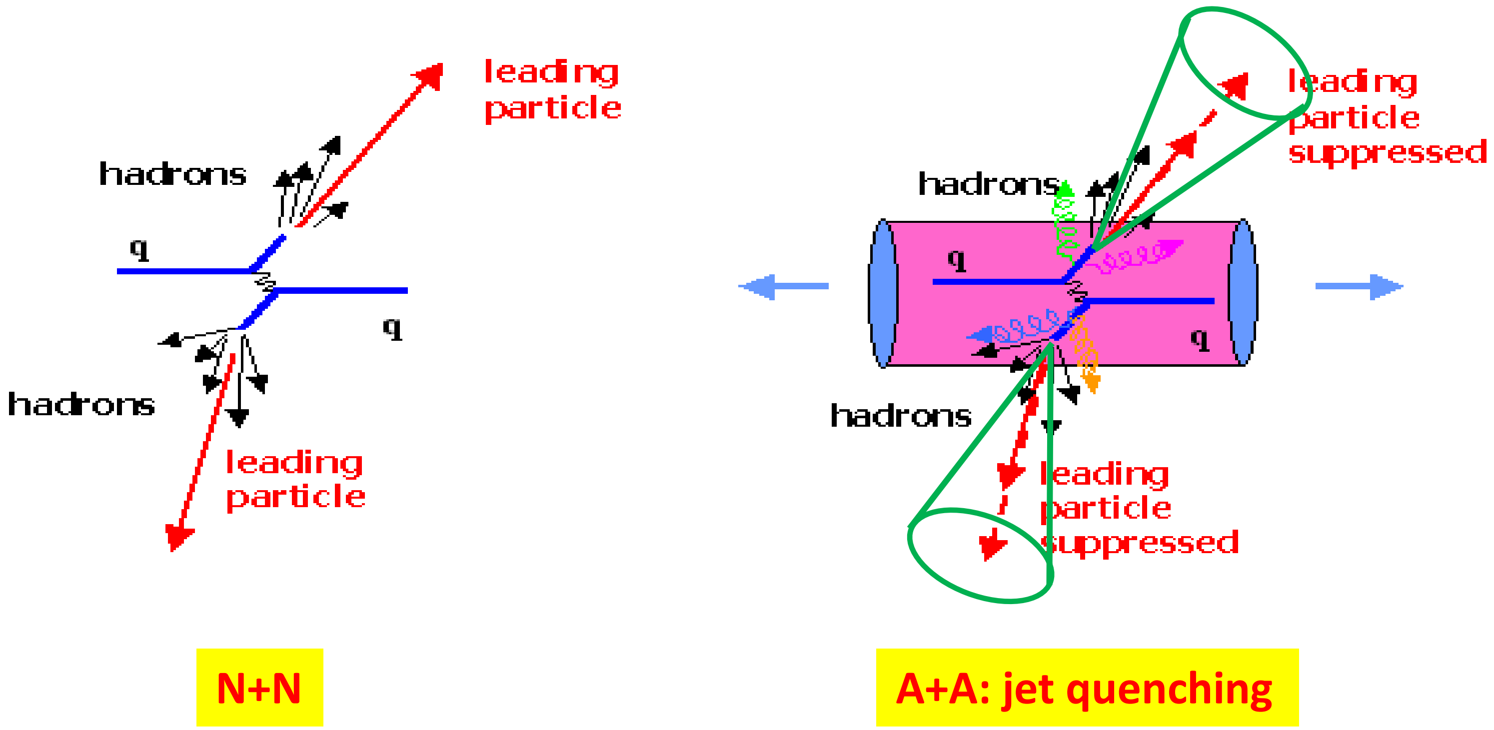
Outline

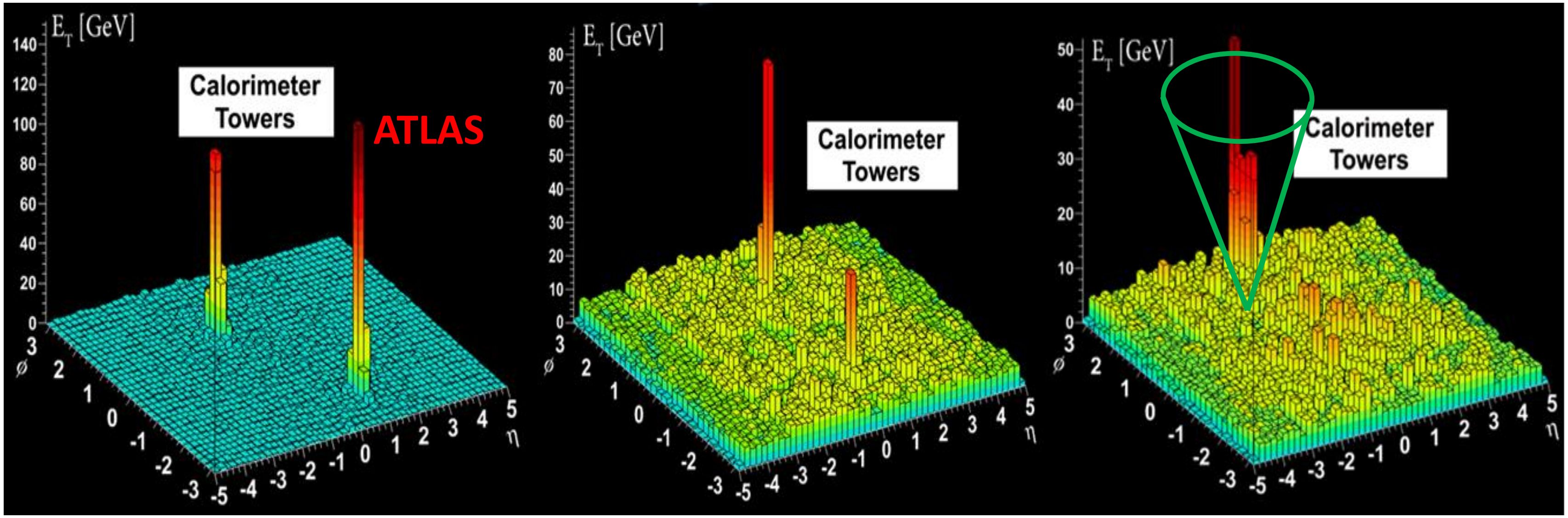
- Introduction and motivation
  - Jet quenching and medium response
- Medium response in AMPT
  - Redistribution of the lost energy from quenched jets
  - Enhancement of the baryon-to-meson ratios around quenched jets
- Summary

Jet quenching



- **Jet quenching includes: (1) jet energy loss, (2) jet deflection and broadening, (3) modification of jet structure/substructure, (4) jet-induced medium excitation (medium response)**

Where does the lost energy go?



- How does the medium respond to the lost energy?
- How does the lost energy redistribute and manifest in final state observables?
- Where to search for the signal of medium response?
- How can we use medium response to probe the medium properties?

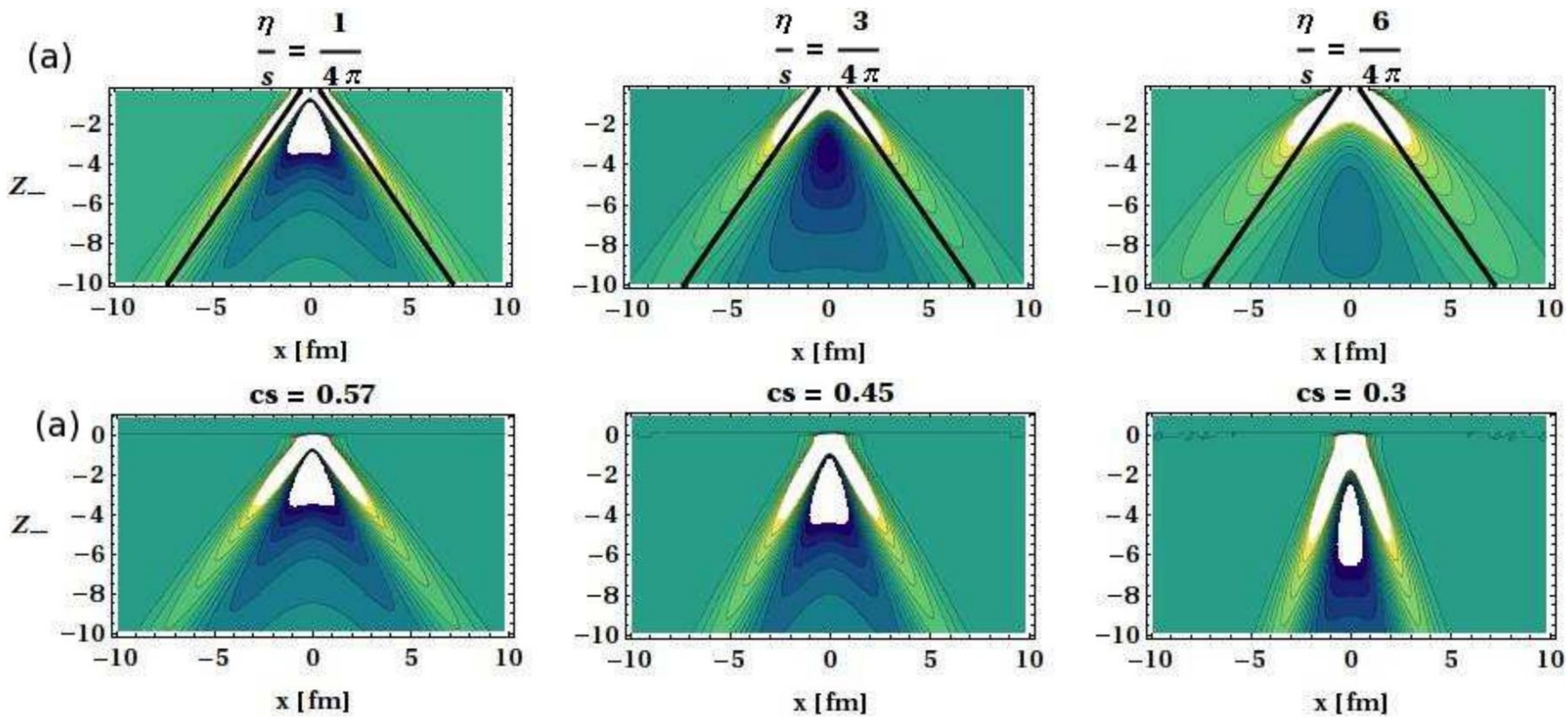
Earlier works on medium response

$$T^{\mu\nu} \simeq T_0^{\mu\nu} + \delta T^{\mu\nu}; \quad \partial_\mu T_0^{\mu\nu} = 0, \quad \partial_\mu \delta T^{\mu\nu} = J^\nu.$$

$$\delta T^{00} \equiv \delta\epsilon, \qquad \delta T^{0i} \equiv g^i,$$

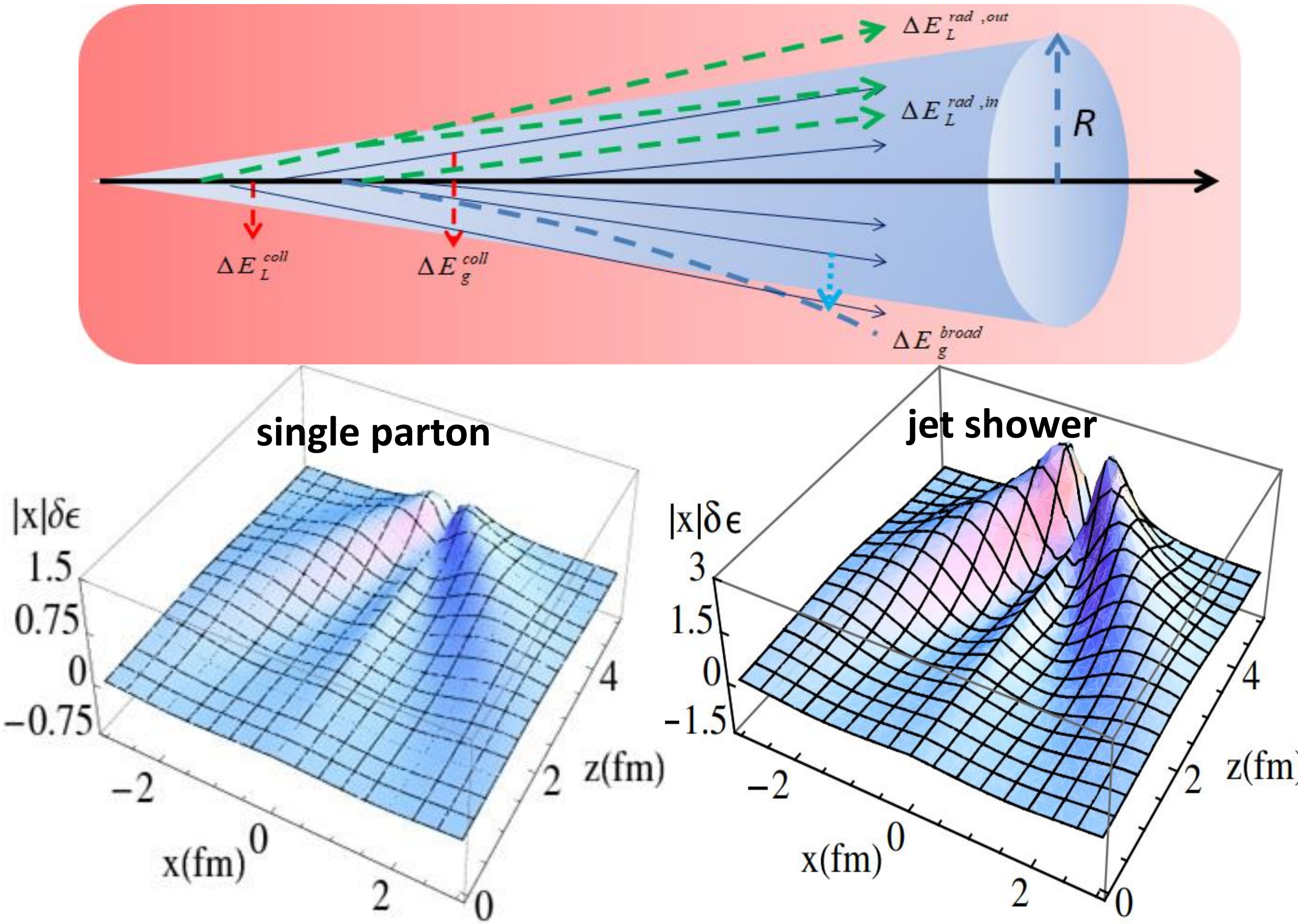
$$\delta T^{ij} = \delta_{ij} c_s^2 \delta\epsilon - \Gamma_s(\partial^i g^j + \partial^j g^i - \tfrac{2}{3}\delta_{ij}\nabla\cdot\vec{g}).$$

Casalderrey-Solana, Shuryak, Teaney, hep-ph/0411315; Stoecker, nucl-th/0406018; Ruppert, Muller, PLB (2005); ...



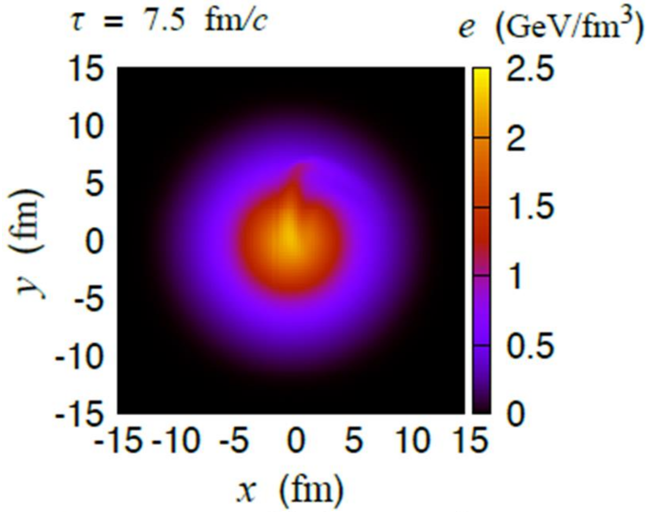
Neufeld, PRC 2009

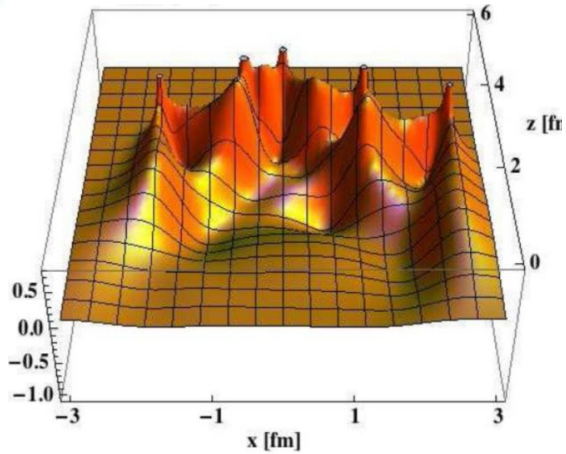
Medium response to jet shower

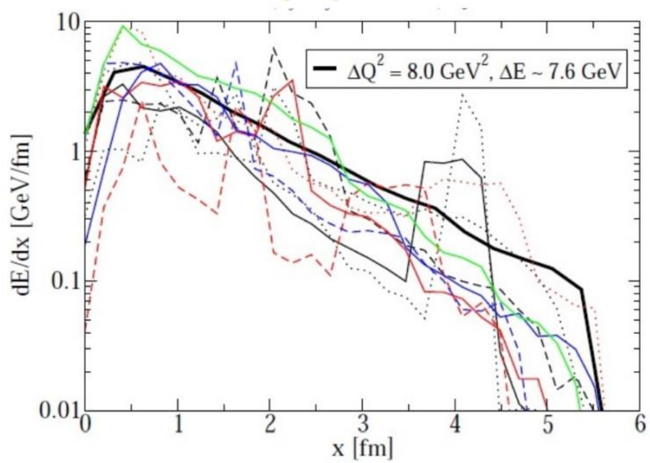


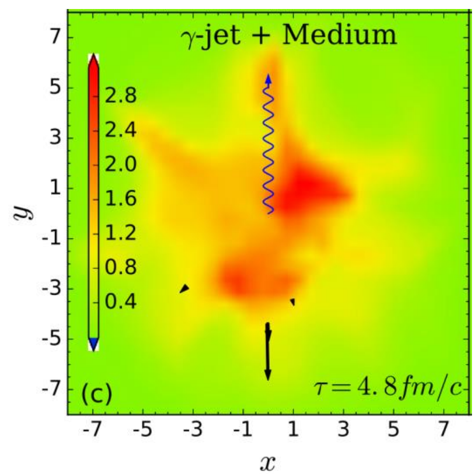
GYQ, Majumder, Song, Heinz, PRL (2009); Neufeld, Muller, PRL (2009)

Complications









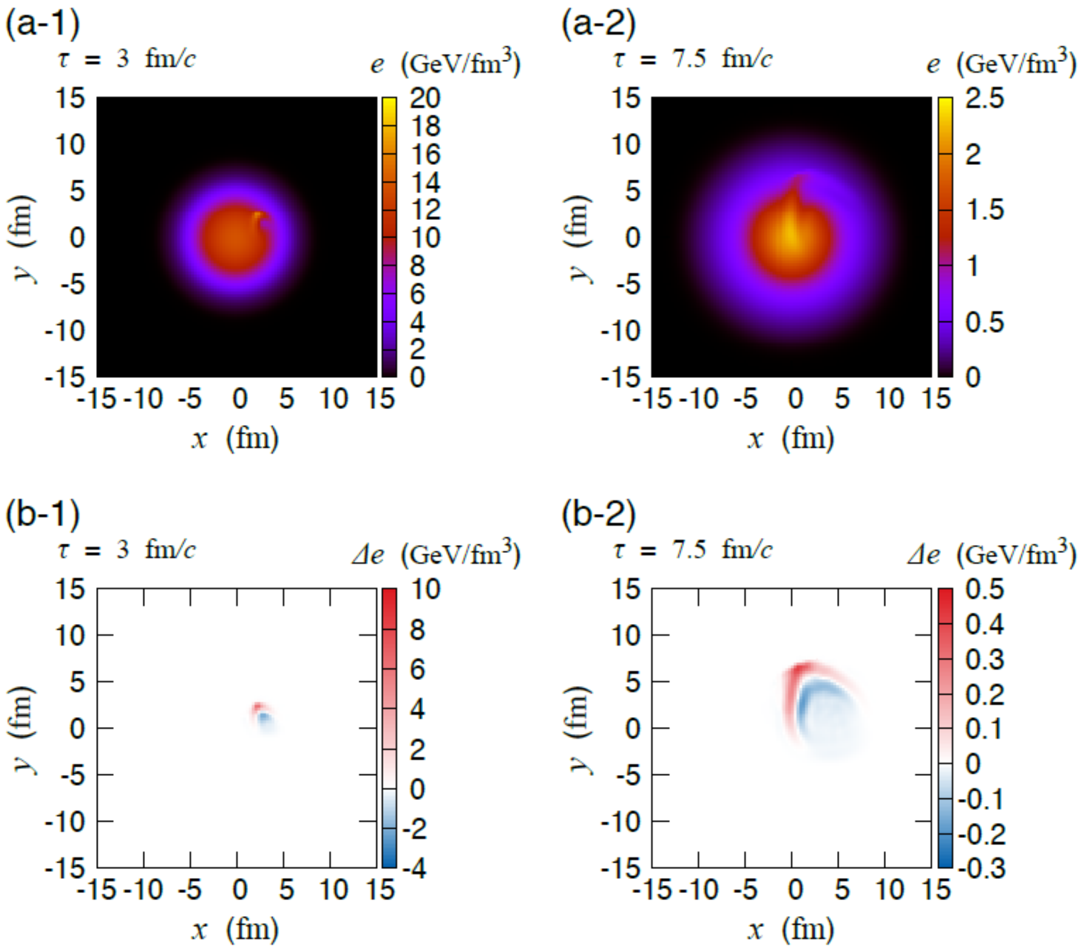
- The flow of the expanding medium can distort the conic structure
- Detailed distributions of the energy and momentum deposition profiles
- Even-by-event fluctuations of jet shower evolution and energy loss
- Large and event-by-event fluctuating background medium

Neufeld, Vitev, PRC 2012; Renk, PRC 2013; Tachibana, Chang, GYQ, PRC 2017; Chen, Cao, Luo, Pang, Wang, PLB 2018

Treatments on medium response

- **Jet + recoil**
  - LBT (He, Luo, Cao, Zhu, Wang, et al, 1503.03313; 1803.06785)
  - JEWEL (Elayavalli, Zapp, Milhano, Wiedemann, 1707.01539; 1707.04142)
  - MARTINI (Park, Jeon, Gale, 1807.06550)
  - JETSCAPE
- **Jet + hydrodynamics**
  - Coupled Jet-Fluid Model (Tachibana, Chang, Qin: 1701.07951; 1906.09562)
  - CoLBT-Hydro (Chen, Yang, Luo, He, Cao, Ke, Pang, Wang, et al, 1704.03648; 2005.09678; 2101.05422; 2203.03683)
  - JETSCAPE (2002.12250)
  - Hybrid Model (Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, 1609.05842)
- **Full Boltzmann**
  - AMPT (Gao, Luo, Ma, Mao, Qin, Wang, Zhang, 1612.02548; 2107.11751; 2109.14314)
  - BAMPS (Bouras, Betz, Xu, Greiner, 1201.5005; 1401.3019)

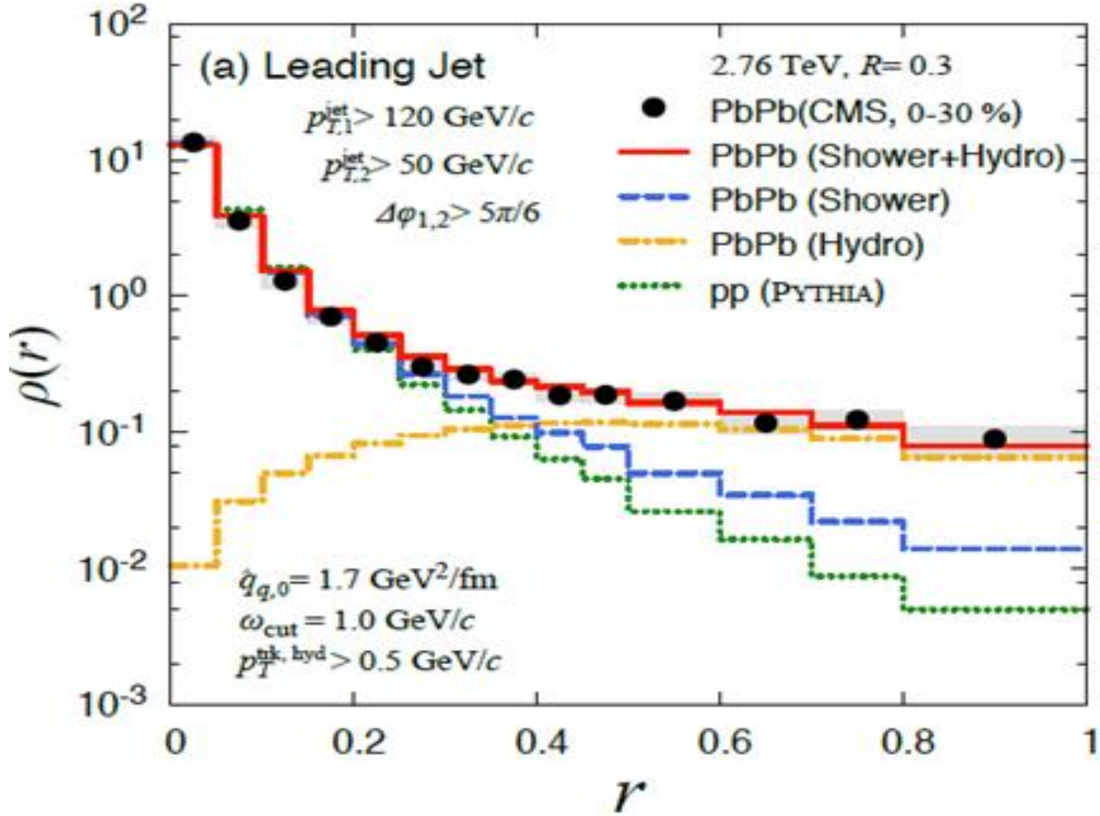
Jet evolution & medium response



- Jet deposits energy and momentum into the medium, and induces V-shaped wave fronts, which develop with time
- The wave fronts carry the energy and momentum, propagates forward and outward, and depletes the energy behind the quenched jet (diffusion wake)
- Jet-induced flow and the radial flow of the medium are pushed and distorted by each other

Chang, GYQ, PRC 2016; Tachibana, Chang, GYQ, PRC 2017; Chang, Tachibana, GYQ, PLB 2020

Signal of jet-induced flow

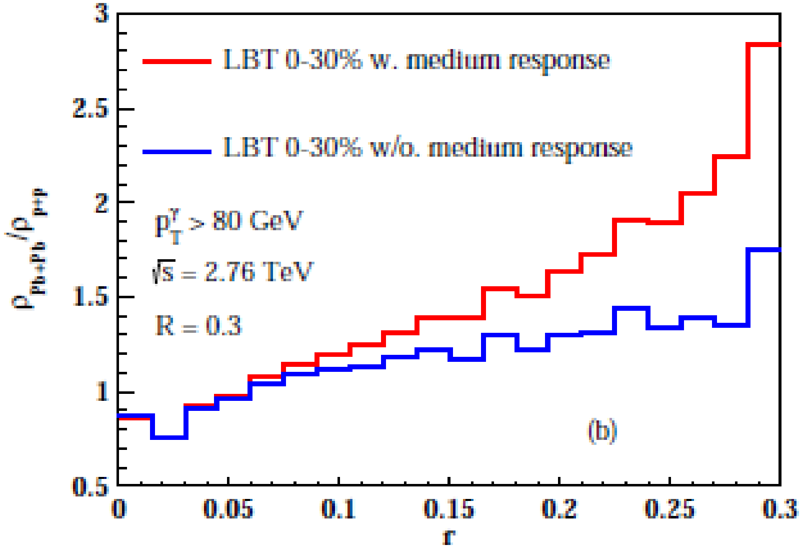


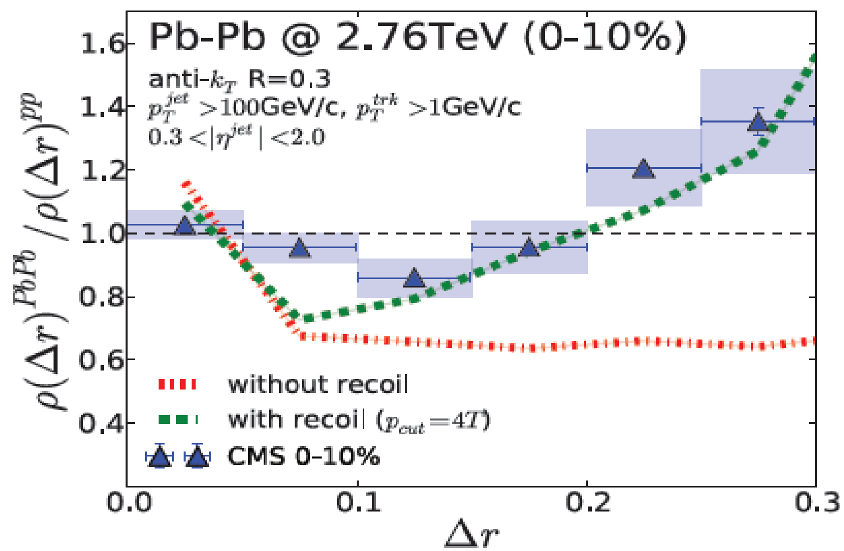
The contribution from the hydro part is quite flat and finally dominates over the shower part in the region from r = 0.4-0.5.

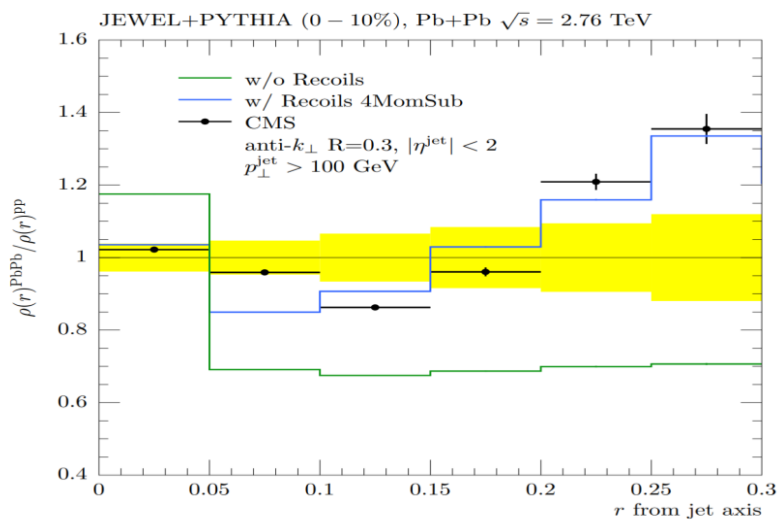
Signal of jet-induced medium excitation in full jet shape at large r.

Chang, GYQ, PRC 2016; Tachibana, Chang, GYQ, PRC 2017; Chang, Tachibana, GYQ, PLB 2020

Effect of jet-induced flow on jet shape



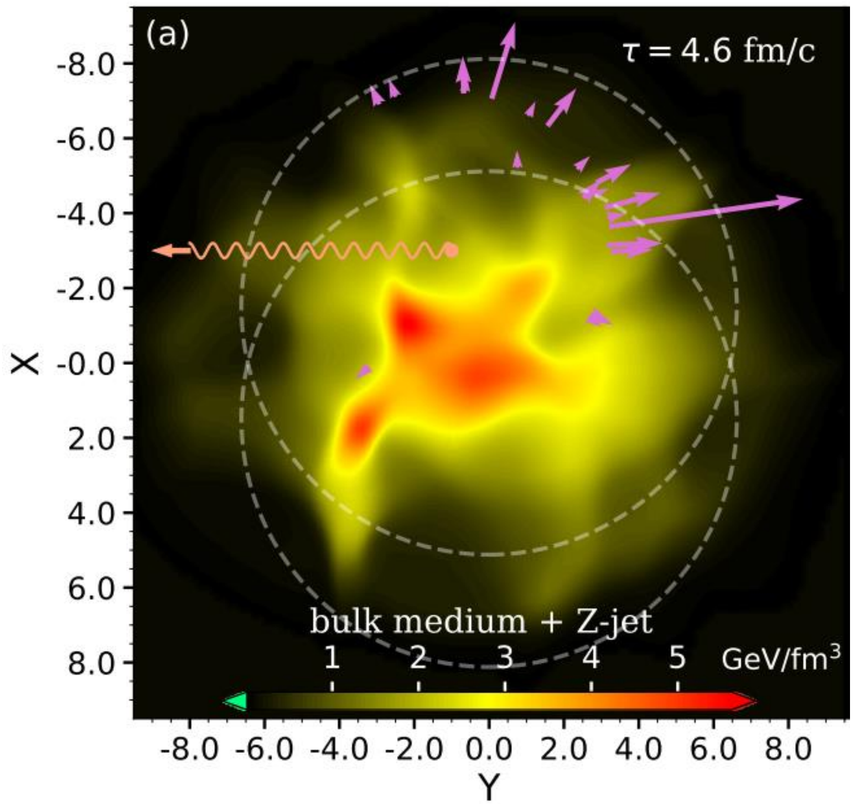


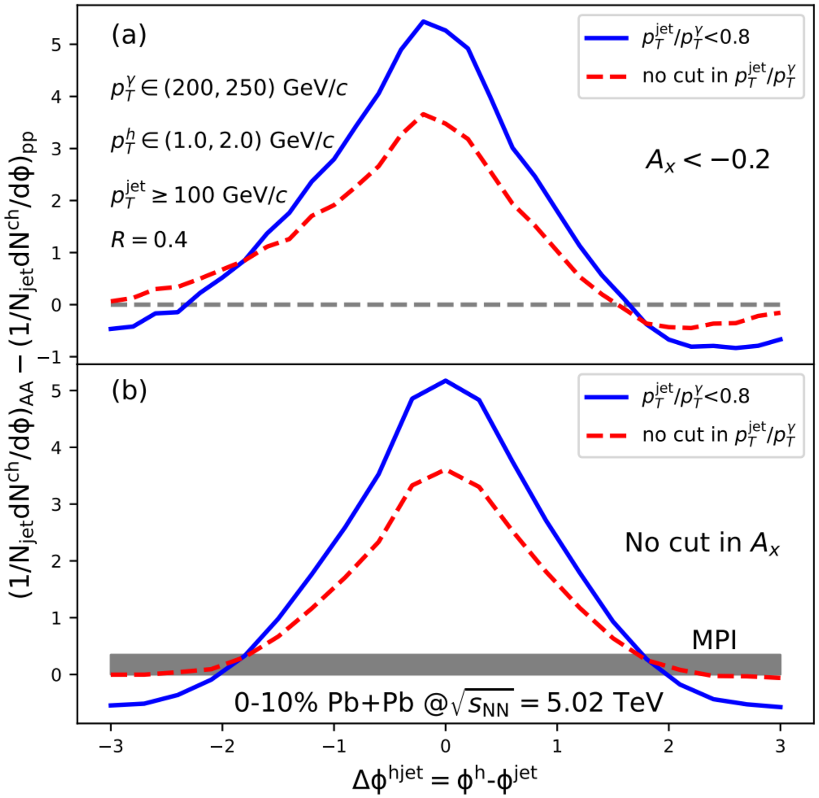


Luo, Cao, He, Wang, PLB 2018;
C. Park, S. Jeon, C. Gale, 2018;
Elayavalli, Zapp, JHEP 2017;

The inclusion of medium response can naturally explains the enhancement of jet shape at larger radius.

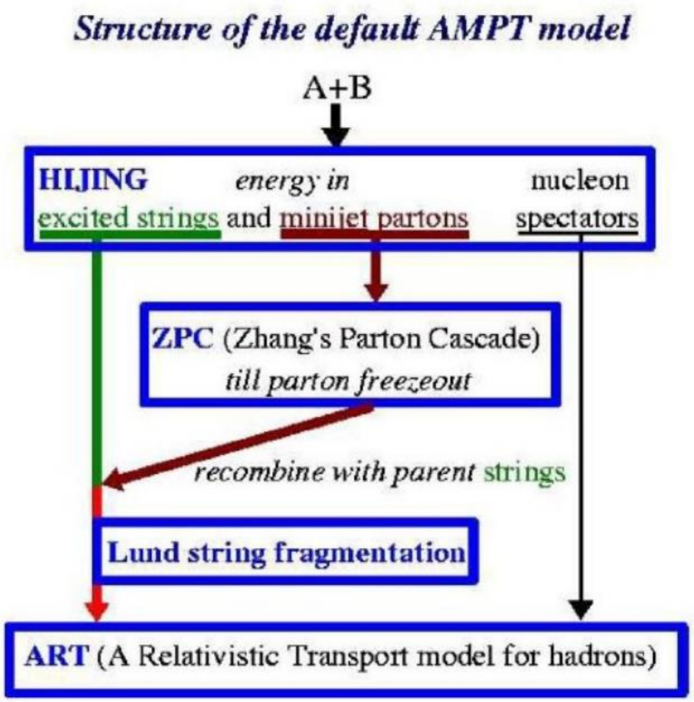
Signal of diffusion wake

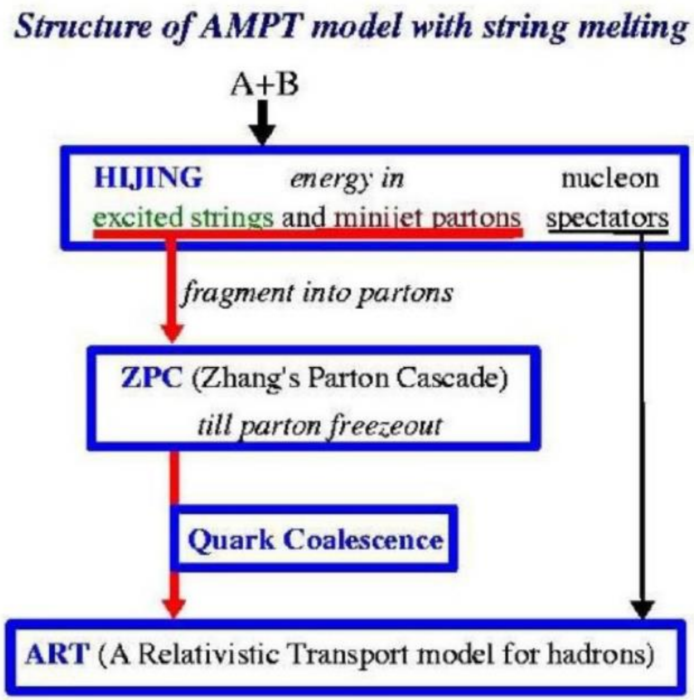




Chen, Yang, He, Ke, Pang, Wang, PRL 2021

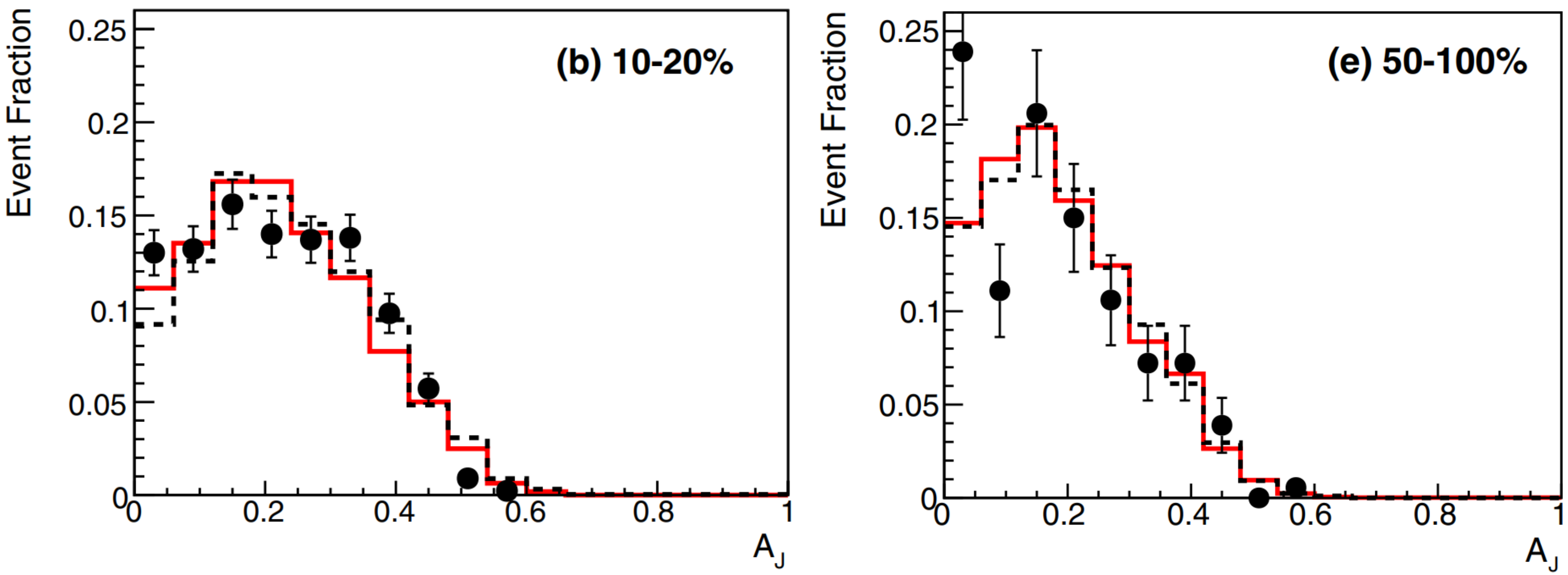
A Mult-Phase Transport (AMPT) Model





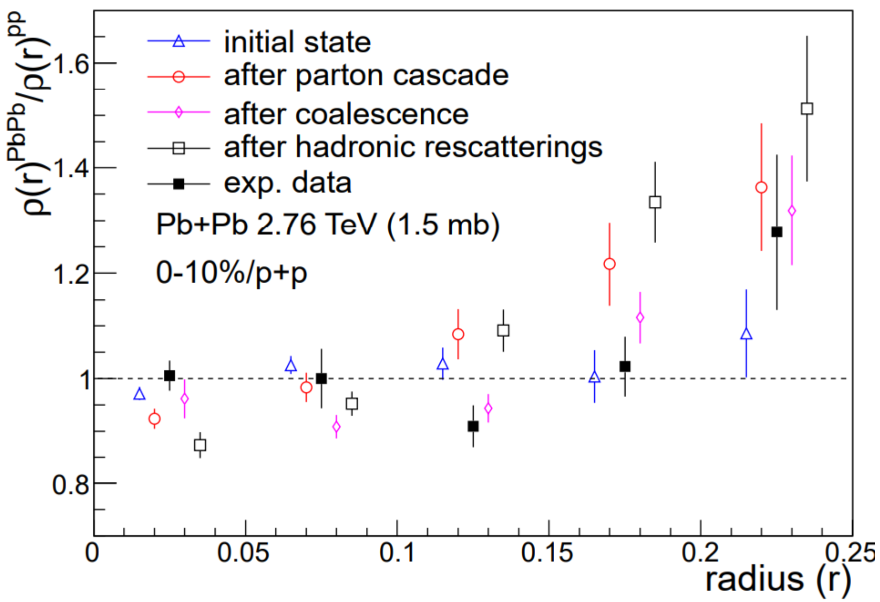
- **AMPT contains 4 main stages: initial condition, parton cascade, hadronization and hadron cascade.**
- **AMPT has been able to describe many bulk and jet observables: flow, dijet and gamma-jet asymmetries, jet shape, jet fragmentation function, etc.**

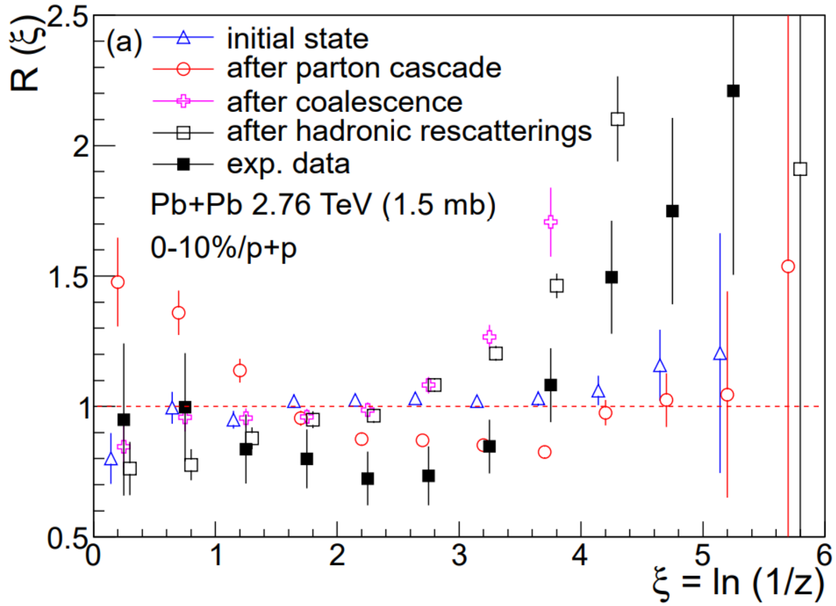
Dijet asymmetry



Jet quenching can explain the nuclear modification of dijet asymmetry in AA collisions.
Stronger interaction (more central collisions and larger cross section) leads to larger nuclear modification effect.

Jet shape and fragmentation function in AMPT





The nuclear modification of jet shape is mainly caused by partonic interaction in the parton cascade stage.

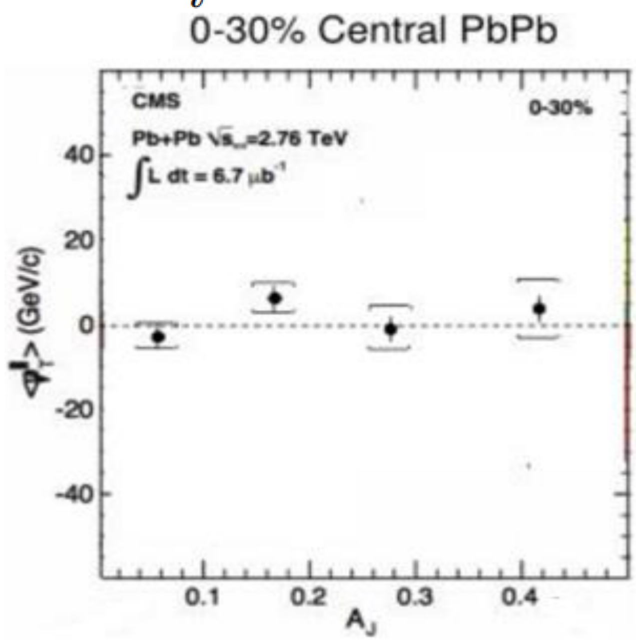
Both partonic interaction and hadronization contribute significantly to the nuclear modification of jet fragmentation function.

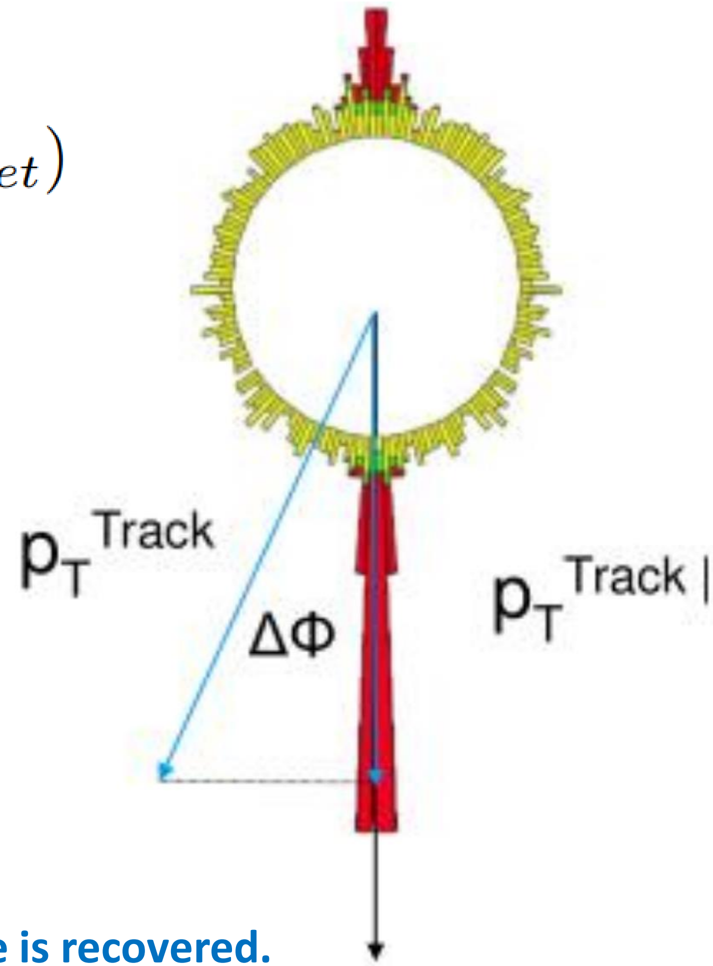
Ma, Phys.Rev.C 88 (2013) 2, 021902; Phys.Rev.C 89 (2014) 2, 024902

Where does the lost energy go?

Project the particle p_T onto the dijet axis:

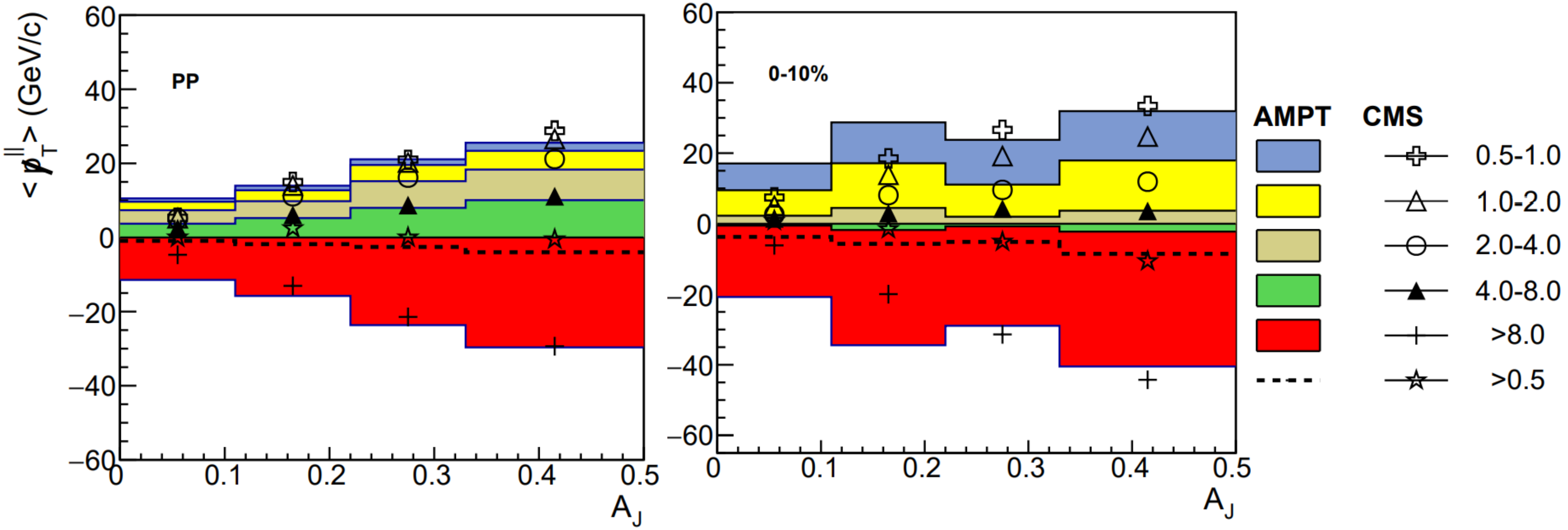
$$\not{p}_T^{||} = \sum_i -p_T^i \cos(\phi_i - \phi_{leading\ jet})$$





Sum over all particles in the event, the p_T balance is recovered.

The p_T balance in dijet events



$$p\!\!\!/_T^{||} = \sum_i -p_T^i \cos(\phi_i - \phi_{leading\ jet})$$

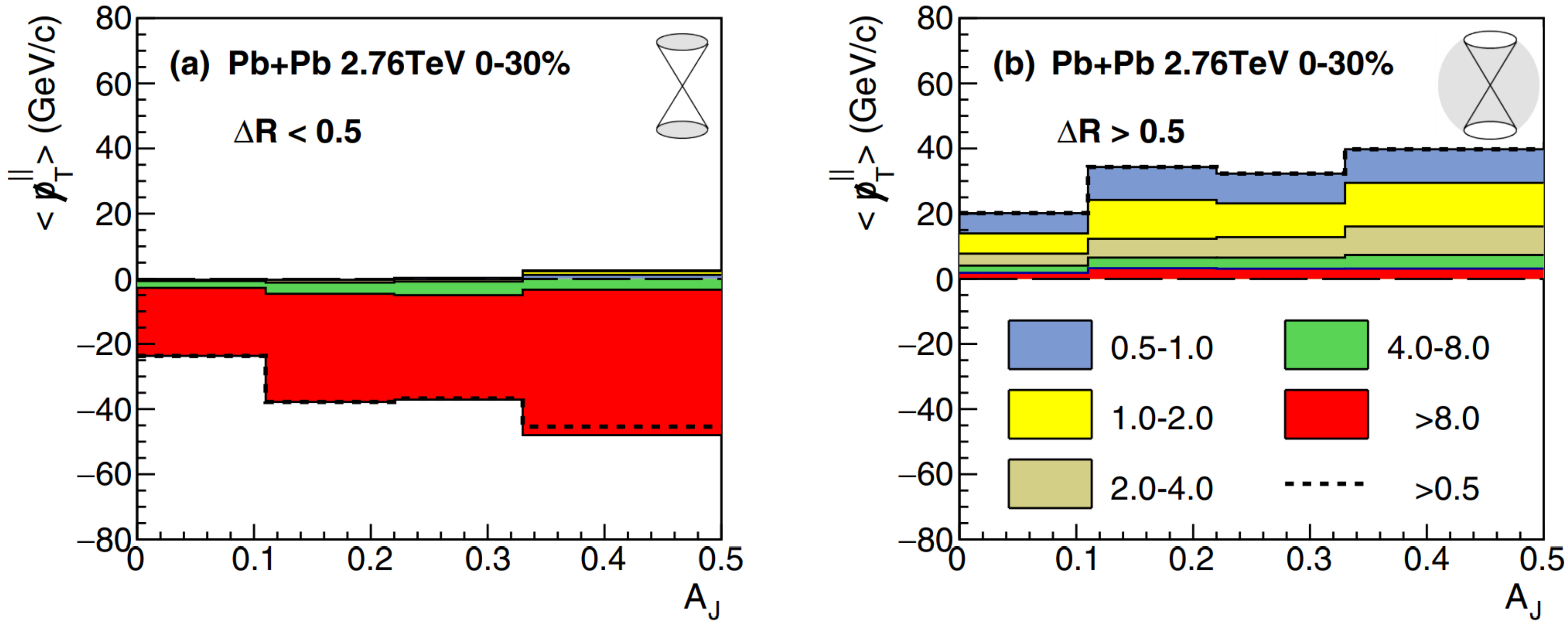
Gao, Luo, Ma, GYQ, Zhang, PRC 2018

Large negative contribution (in the leading jet direction) from hard hadrons (p_T > 8 GeV) is balanced by the positive contributions from hadrons with p_T = 0.5-8 GeV.

For pp collisions, the p_T imbalance in asymmetric dijet events is mostly compensated by p_T =2-8GeV hadrons.

For AA collisions, the p_T imbalance in asymmetric dijet events is mostly compensated by soft (p_T < 2.0 GeV) hadrons.

In-cone and out-of-cone contributions



The in-cone contribution to the projected transverse momentum is dominated by hard hadrons (p_T > 8.0 GeV).

The out-of-cone contribution is dominated by soft hadrons (p_T < 2.0 GeV/c).

A significant amount of the lost energy from quenched jets is carried by soft hadrons at large angles away from jet axis.

Gao, Luo, Ma, GYQ, Zhang, PRC 2018

How does the medium response affect the chemical compositions of particles around quenched jets?

- Jet-induced medium response and flow can affect both the momentum and angular distributions of particles around quenched jets.

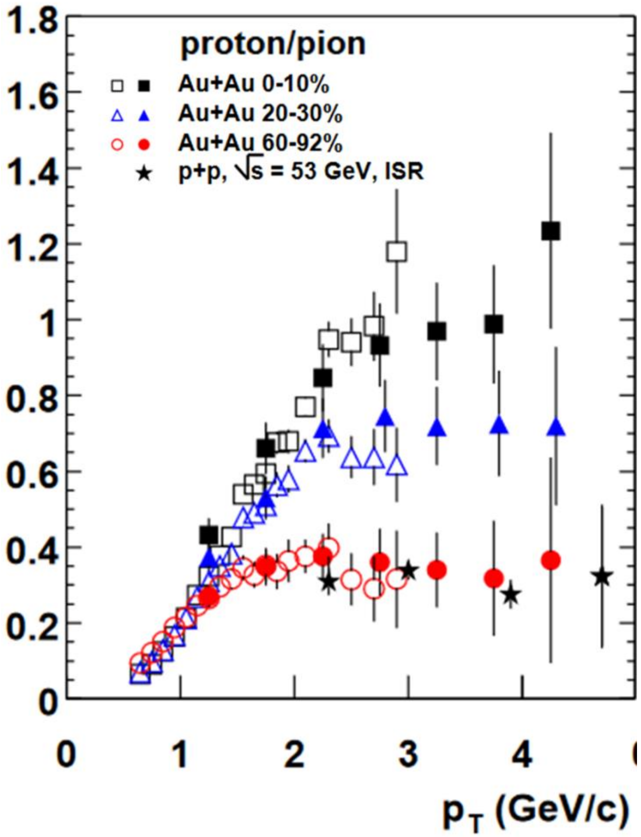
- Due to the interaction with medium, the lost/deposited energy will be (partially) thermalized.

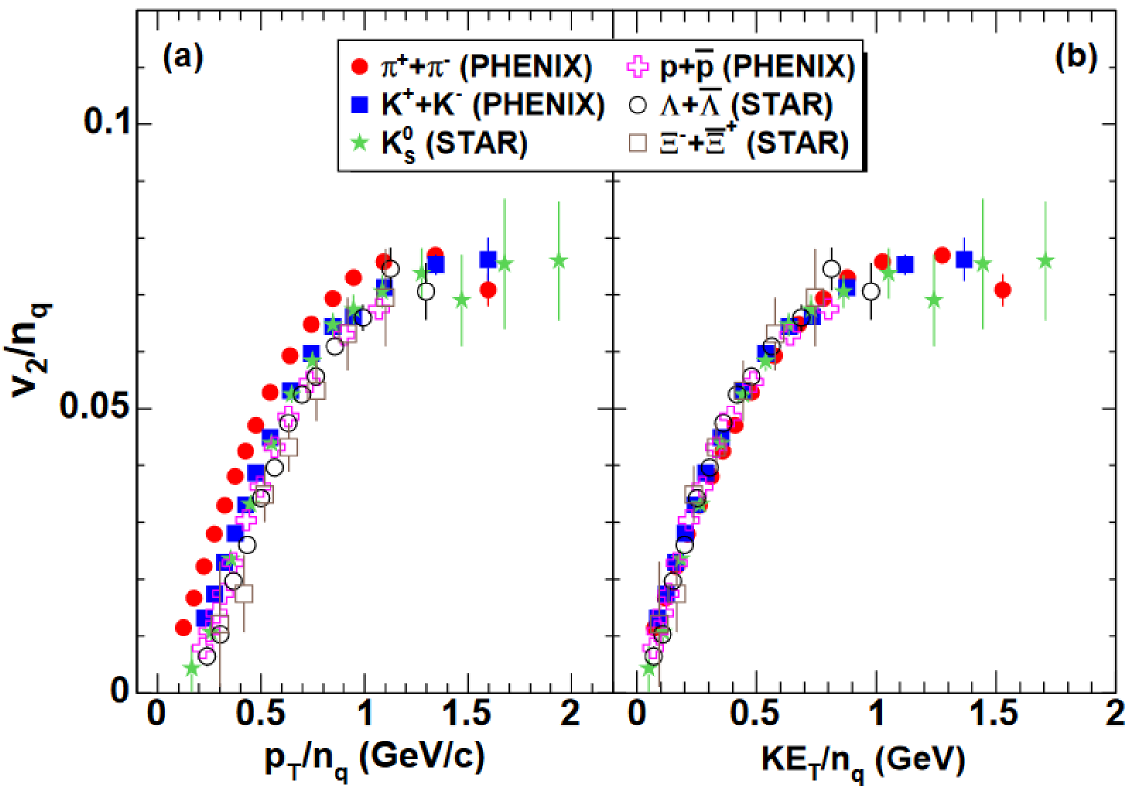
- The particles (and chemical compositions) produced from thermalized energy should be different from those from vaccum-like energies.

- As a result of the coalescence of jet-excited partons, jet-medium interaction can lead to **the enhancement of baryon-to-meson ratio at intermediate p_T around the quenched jets.**

- Since the lost energy can flow to large angles, we expect the enhancement should **depend on the distance with respect to jet axis.**

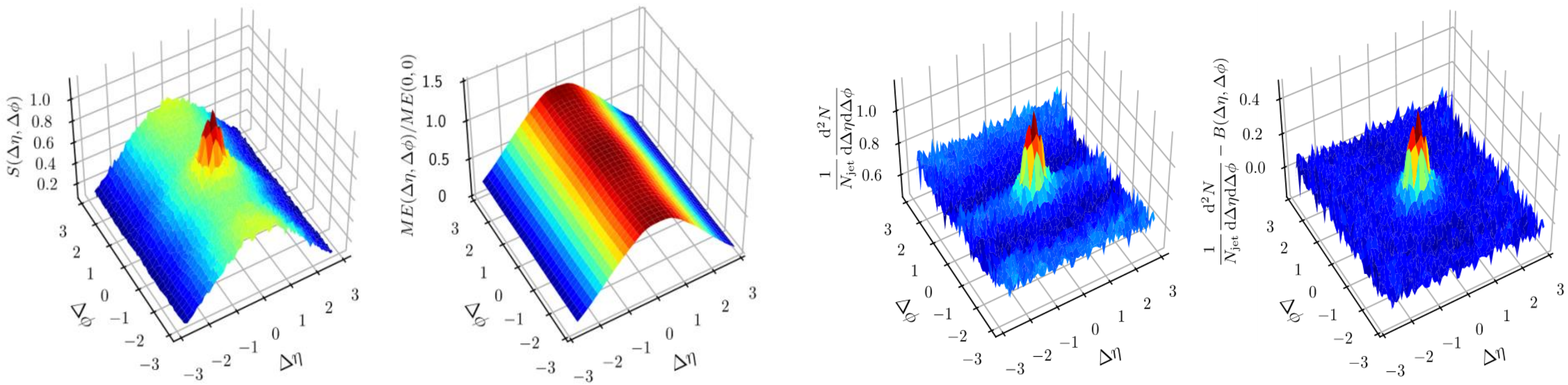
B/M enhancement & v_2 NCQ scaling of bulk matter





Coalescence of thermal partons from QGP can naturally explain the NSQ scaling of v_2 and the enhancement of baryon-to-meson ratio at intermediate p_T.

Jet-particle correlations



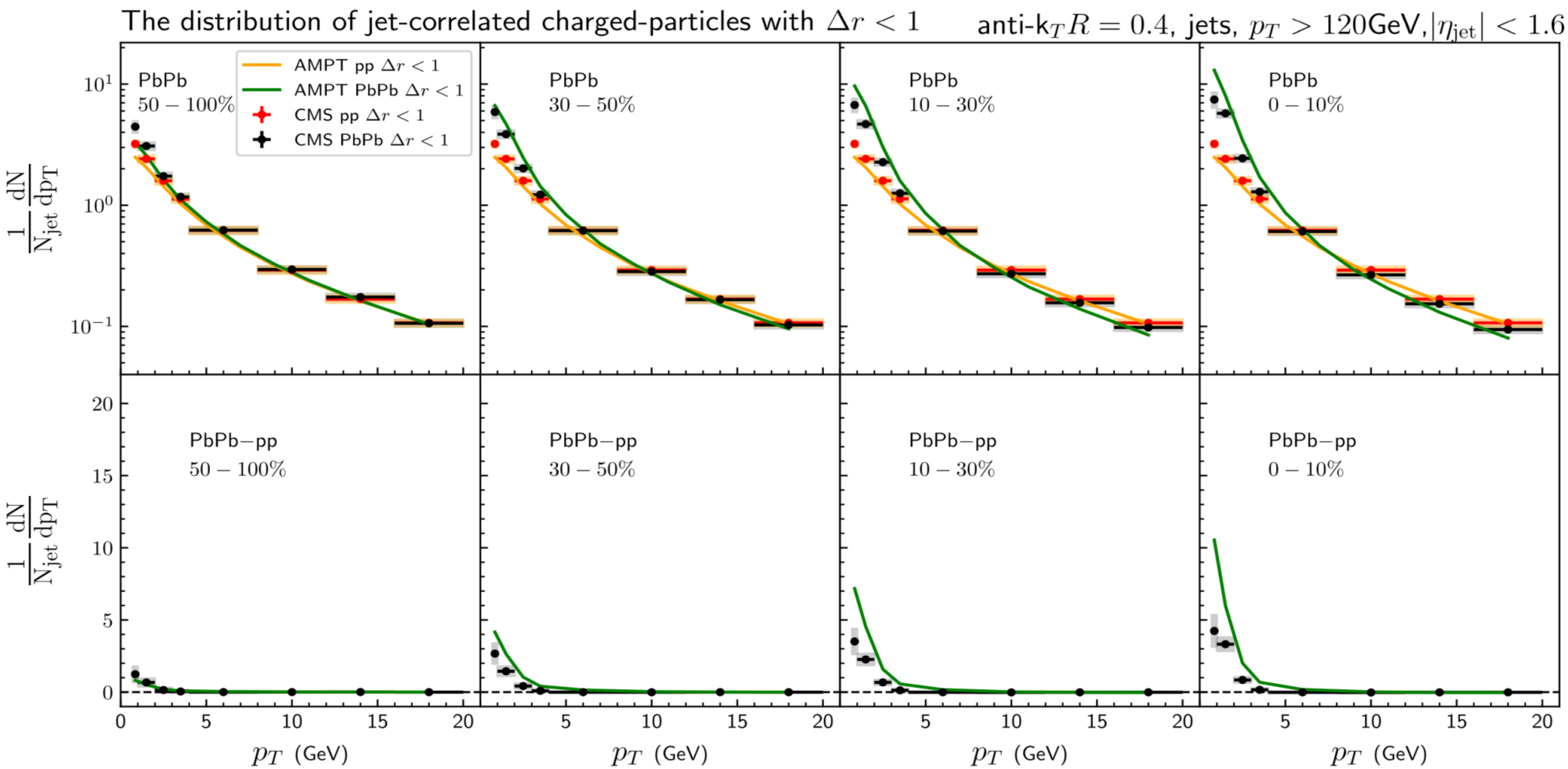
$$\frac{1}{N_{\mathrm{jet}}}\frac{d^2N}{d\Delta\eta d\Delta\phi} = \frac{ME(0,0)}{ME(\Delta\eta,\Delta\phi)}S(\Delta\eta,\Delta\phi) \Rightarrow \frac{d^3N}{dp_T d\Delta\phi d\Delta\eta}$$

$$\frac{dN}{dp_T} = \int d\Delta\phi \int d\Delta\eta \frac{d^3N}{dp_T d\Delta\phi d\Delta\eta}\bigg|_{\Delta r<1}$$

$$\frac{dN}{d\Delta r} = \int d\Delta\phi \int d\Delta\eta \int dp_T \frac{d^3N}{dp_T d\Delta\phi d\Delta\eta}\delta(\Delta r - \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2})$$

Luo, Mao, GYQ, Wang, Zhang, 2109.14314

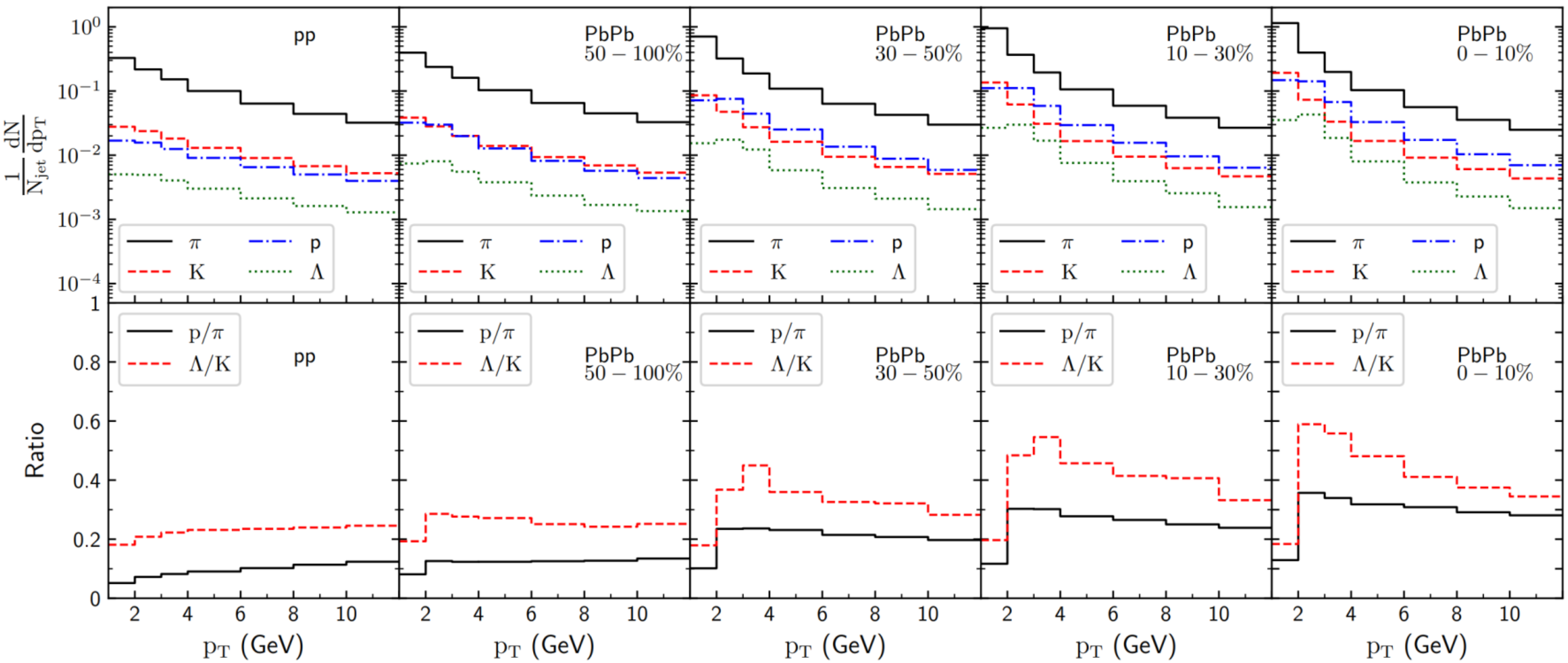
Jet-induced particle yield around jets



Jet quenching leads to the enhancement of soft particles and the suppression of hard particles around the jets. Such effect is more pronounced for more central collisions.

Luo, Mao, GYQ, Wang, Zhang, 2107.11751

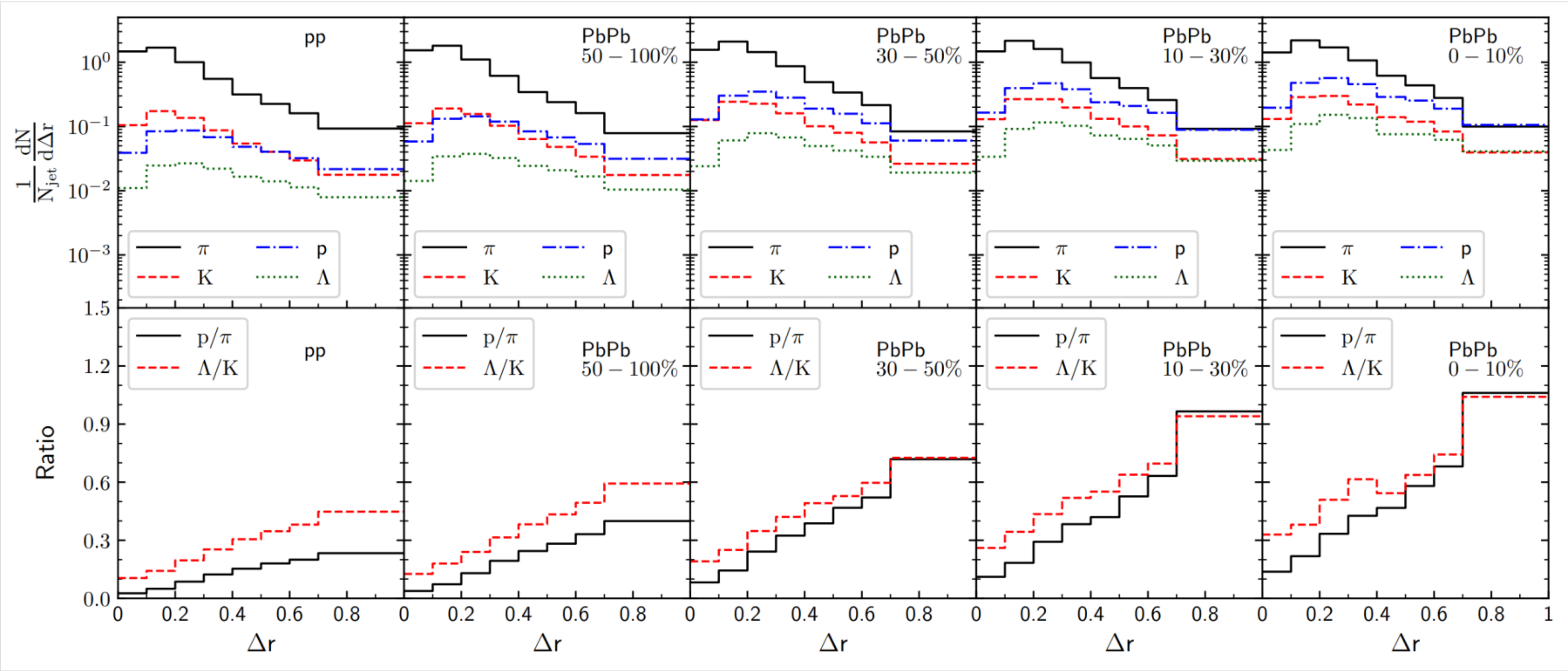
B/M enhancement around jets: p_T dependence



We find a strong enhancement of B/M ratios for associated particles at intermediate p_T around the quenched jets, due to the coalescence of jet-excited medium partons.

Luo, Mao, GYQ, Wang, Zhang, 2109.14314

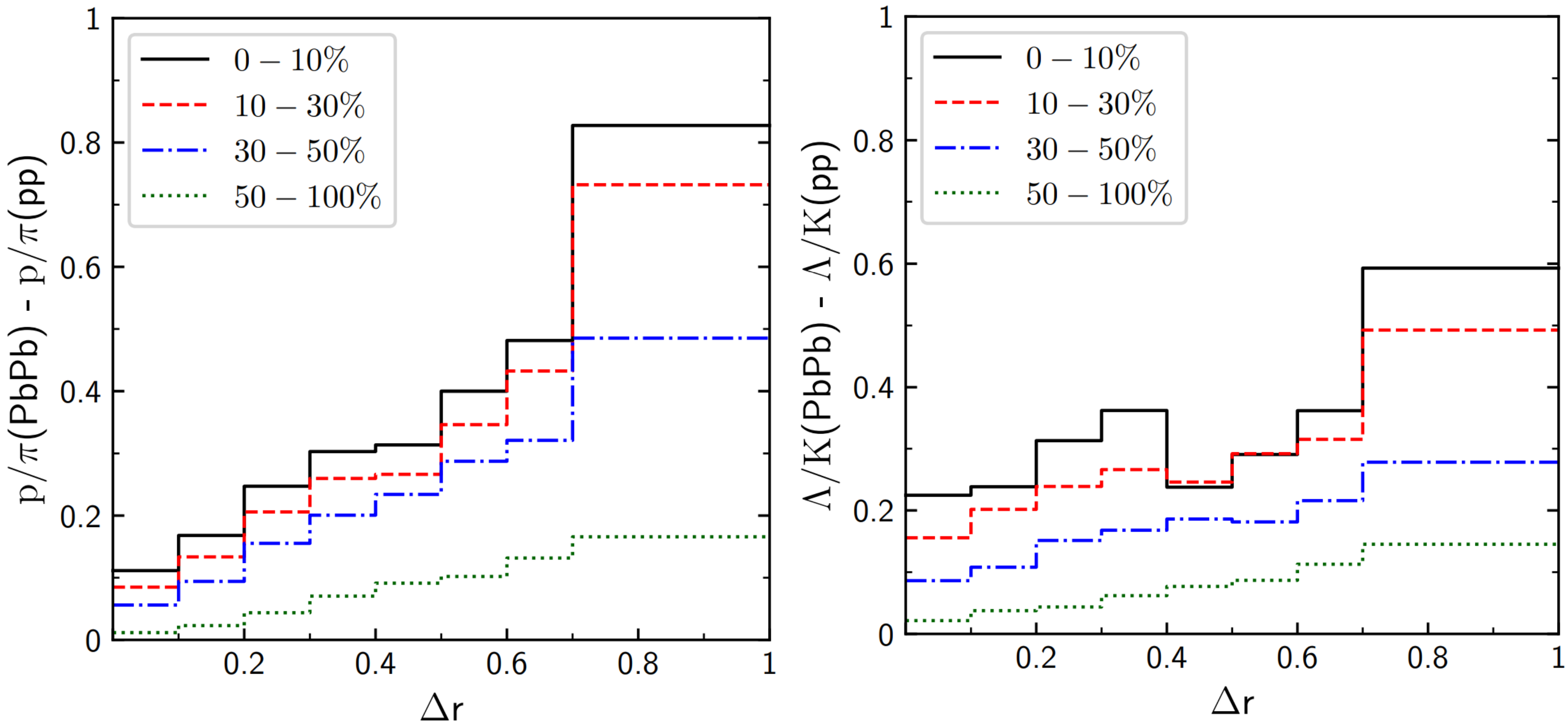
B/M enhancement around jets: radial dependence



For intermediate p_T (2-6GeV) regime, the enhancement of jet-induced B/M ratios is stronger for larger distance because the lost energy from quenched jets can diffuse to large angle.

Luo, Mao, GYQ, Wang, Zhang, 2109.14314

B/M enhancement around jets: radial dependence



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Luo, Mao, GYQ, Wang, Zhang, 2109.14314

Summary

- **Medium response is an important aspect of jet quenching.**
- **AMPT model provides a versatile tool to study the bulk evolution as well as jet-medium interaction.**
- **The energy deposited by the quenched jet is carried by soft particles at large angles.**
- **The enhancement of the baryon-to-meson ratio at intermediate p_T around the quenced jets**
  - **A unique signature of medium response.**
  - **Does not depend on the model details of jet quenching and parton coalescence.**
- **Need to include more ingredients such as inelastic scattering processes (or use more sophisticated model) for more precise description/prediction.**
- **Use medium response to probe EOS and transport properties of QGP.**